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FORECASTING STRONG WINTER WINDS OVER PUERTO RICO AND THE VIRGIN ISLANDS

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ABSTRACT

Wintertime synoptic situations leading to the occurrence of strong surface winds over coastal waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and the northern Leeward Islands are discussed. Six-hourly average wind speeds for the oceanic areas adjacent to Puerto Rico are obtained from ship reports and related to the surface pressure gradient. The onset of surface winds of 20 knots or greater is found to follow the crossing of the east coast of the United States by a migratory anticyclone with above critical central pressure, or the occurrence of strong trade winds above the gradient level at San Juan, P. R., as a nonmigratory anticyclone intensifies. These results are combined into objective forecasting rules for predicting the onset of strong winds 12 to 24 hours ahead.

1. INTRODUCTION

Sailing schooners and small motor vessels engage in commerce between Puerto Rico and the Lesser Antilles amounting to more than $13 million annually. Warnings for strong winds and rough seas are important in protecting these small craft as well as fishing and pleasure boats. This study develops a procedure for predicting the onset of strong winds sufficiently in advance so that warnings may be issued and distributed in time to be effective. The study is limited to the winter months and to a forecast area bounded by the parallels 17° and 22° N. and the meridians 60° and 70° W. (fig. 4). This area includes the adjacent waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and northern Leeward Islands for which Small Craft Warnings are issued. Forecasting strong winds over this area presents a problem due to the lack of reliable surface wind reports and sparsity of data over critical oceanic areas.

Initially, the study is concerned with the relationship between wind and pressure gradient over the forecast area. After determining this relationship the study concentrates on the pressure gradient and uses it as a measure of the wind strength. Finally, the study derives an objective method for forecasting the onset of strong winds 12 to 24 hours from the time of the latest synoptic surface map.

Past experience indicates that strong winds over the forecast area in winter are usually caused by intense high pressure systems to the north. Deep Lows in the western North Atlantic usually move on a track too far north to cause strong winds in the forecast area; however, swells generated by these storms occasionally do reach the area. Strong winds of short duration may be caused by thunderstorms, but these are rare in winter and are not treated in this paper. Thus the only significant synoptic situation likely to cause strong winds in the winter is related to a high-pressure system centered north of the forecast area. Anticyclones most likely to create strong winds in the forecast area may be divided into two types. These are migratory cold Highs moving eastward off the coast of the United States and semipermanent warm Highs over the western North Atlantic.

In marine terminology a strong wind is equivalent to Beaufort Force 6 (22 to 27 knots) and Small Craft Warnings are issued whenever this condition is expected in the forecast area. Although the lower limit of a strong wind by this definition is 22 knots, this study uses 20 knots since ship reports, which constitute the main source of surface wind data, are entered on the surface map to the nearest 5 knots.

2. SELECTION OF DATA

SURFACE WIND

Land stations with representative surface wind reports would have greatly simplified the tabulating of data. Unfortunately, there are no land stations in Puerto Rico or the Virgin Islands that have an unobstructed exposure and that could be considered representative of the surface wind conditions over the open sea. The wind speed falls off very rapidly a short distance inland from the coast because of friction, land and sea breeze effects, and terrain and vegetation. For example, on January 21, 1957, when ship reports in the vicinity of Puerto Rico indicated winds of 20 to 25 knots, an anemometer mounted on a mast 76.7 feet above sea level at the Naval Air Station in San Juan recorded winds of 5 to 10 knots with a maximum of 16 knots. On the same day, Isla Verde Airport to the east of San Juan recorded winds that generally ranged between 5 and 12 knots with a maximum of 18 knots. It was therefore necessary to turn to ship reports to obtain reliable surface wind data for this study.

Representative surface winds were obtained by averaging ship reports in the forecast area (fig. 4). The area extends farther to the north than to the south of Puerto Rico because synoptic developments creating high winds during the winter almost invariably approach from the north. Data for the months December through March of 1955–56 and 1956–57 were used as the development sample. Wind speeds were averaged for each 6-hourly surface map during these periods whenever surface ship reports were available in the area. Great care was taken to ascertain that reports were representative of the wind field. This was done by checking the past history of ships for wind accuracy and by discounting ships' reports that were obviously in error. Data from maps having only one ship in the area were not tabulated when the data were obviously erroneous.

PRESSURE GRADIENT

After the surface wind data had been obtained, the next step was to measure the surface pressure gradient. This was measured by taking the pressure difference in millibars over the fixed distance of 10° of latitude from 15° N. to 25° N. along a north-south line across Puerto Rico. Because of the prevailing easterly wind flow in the Caribbean, a north-south line is almost always perpendicular to the isobars. The reason for choosing this distance with its longer segment lying north of Puerto Rico was to emphasize the data to the north of the island. Before this particular measurement of the gradient was selected, alternative measurements that attempted to make full use of available land stations had proved unsatisfactory.

Pressure gradient measurements over the selected distance were taken from each 6-hourly surface map for the winters of 1955–56 and 1956–57. This pressure gradient, hereafter designated by Δp, was measured independently of the surface wind speed to eliminate, as far as possible, the introduction of bias. Measurements of Δp by different forecasters varied by less than 1 millibar; pressure readings at latitude 15° N. were considered to be very reliable in view of the pressure observations at land stations in the Lesser Antilles; readings at 25° N., being farther away from land were more subjective, but nevertheless were fairly reliable due to the averaging effect of numerous ship reports.

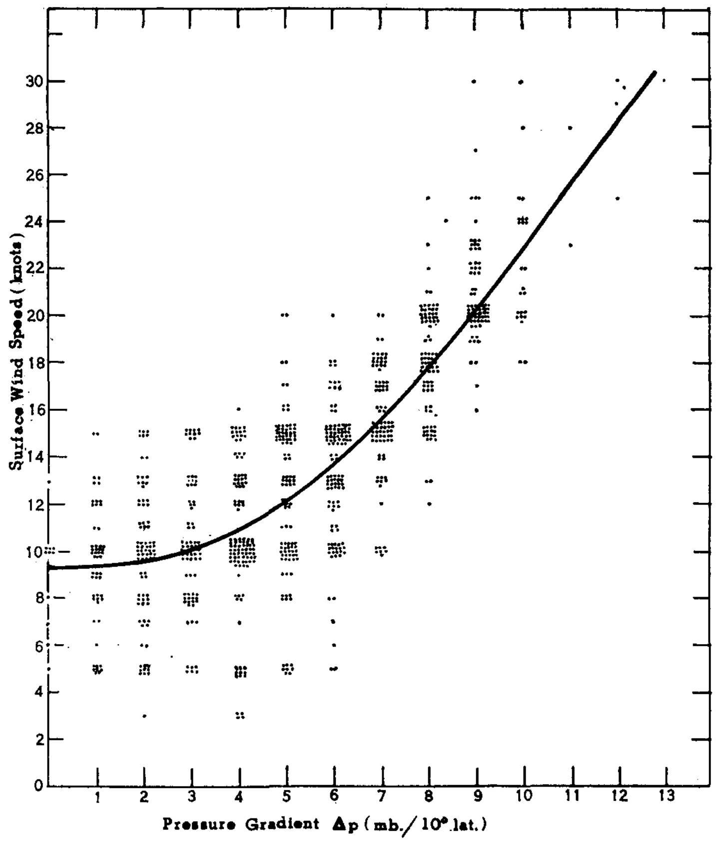

FIGURE 1.—Scatter diagrams showing correlation between pressure gradient (Δp) and surface wind speeds for winters of 1955–56 and 1956–57.

3. RELATION OF PRESSURE GRADIENT TO THE SURFACE WIND

Figure 1 shows the relationship of the pressure gradient (Δp) to the surface wind speed based on data for the winters 1955–56 and 1956–57. The direct correlation between Δp and surface wind speed is well marked. As an example, $\Delta p=3$ corresponds in general to a surface wind speed between 8 and 13 knots, $\Delta p=8$ corresponds to 15 to 20 knots, and $\Delta p=10$ corresponds to 20 to 25 knots.

A value of 20 knots was selected as the critical wind speed requiring Small Craft Warnings in the forecast area. Figure 1 shows that $\Delta p>8$ almost always results in surface wind speeds of 20 knots or greater. This can be more readily seen in figure 2 which shows that—

$\Delta p \geq 9$ corresponds to speeds of 20 knots or greater 88 percent of the time;

$\Delta p \leq 7$ corresponds to speeds of less than 20 knots 99 percent of the time; and

$\Delta p=8$ is marginal corresponding to speeds of 20 knots or higher 33 percent of the time.

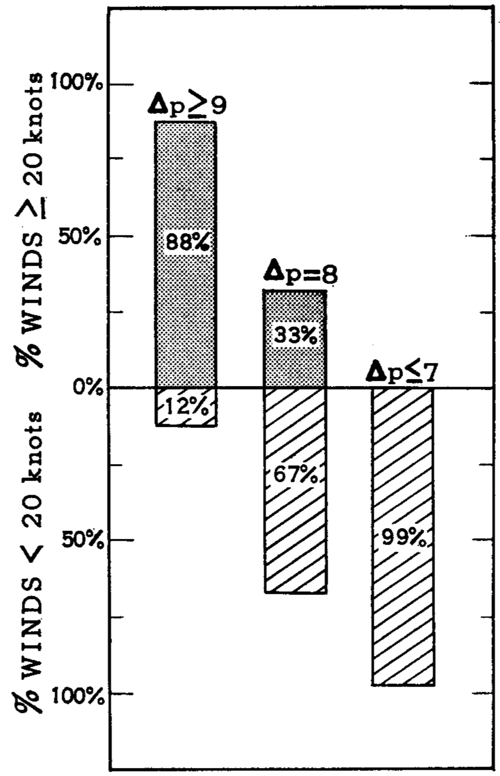

FIGURE 2.—Percentages of surface winds above or below 20 knots for various pressure gradients (Δp).

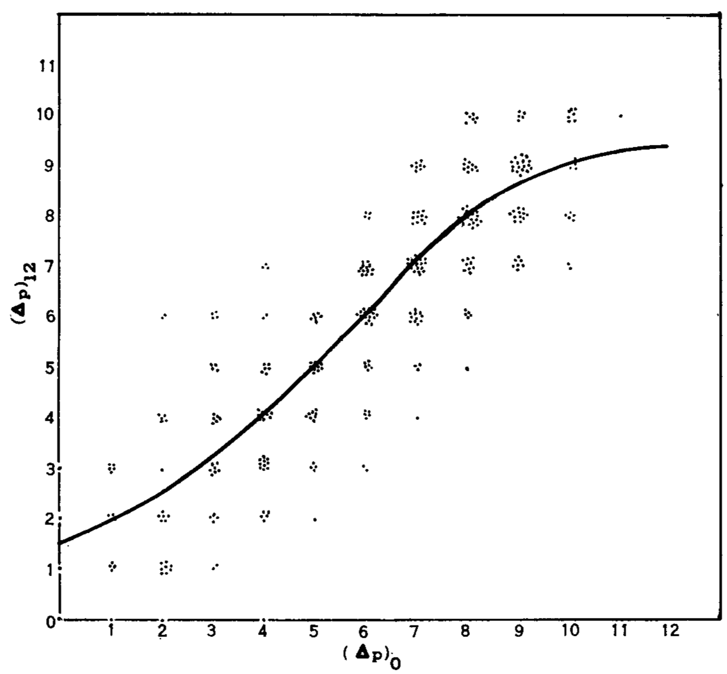

FIGURE 3.—Scatter diagram showing relationship between current pressure gradient $(\Delta p)_0$ and pressure gradient 12 hours later $(\Delta p)_{12}$ for winter 1956–57.

Thus, with $\Delta p \geq 9$, Small Craft Warnings are necessary and for a $\Delta p \leq 7$ no warnings are needed. Occasions when winds of 20 knots or higher occurred with $\Delta p = 8$ were investigated separately. For these occasions, if in conjunction with semipermanent Highs, the upper winds provided a worthwhile forecast parameter. This is discussed in section 6.

To determine the persistency of a given pressure gradient, scatter diagrams were plotted for current Δp against its value 6, 12, 18, and 24 hours later. The scatter diagram for a 6-hour lag showed that Δp would not vary by more than 1 millibar. The scatter diagram for a 12-hour lag (fig. 3) also shows good correlation and that the 12-hour change in Δp rarely exceeds 2 millibars. This slow change in Δp normally precludes the sudden occurrence of gradients associated with strong winds.

4. SELECTION OF FORECAST PARAMETERS

As previously stated, the forecast problem is to predict the onset of strong winds over the forecast area in time to issue early warnings. Forecasts much beyond 24 hours are generally unnecessary, and forecasts for less than 6 hours provide too little time to issue warnings. Therefore, it was decided to concentrate this study on a forecast for a minimum of 12 hours, and preferably for 24 hours, subsequent to the time of the latest surface map. Subject to these requirements, the first step was to select parameters for a forecast method to be valid for the months of December through March.

Parameters selected for the forecast study were those that seemed most successfully to measure conditions causing the onset or continuance of strong winds over the forecast area. These were: (1) location and intensity of migratory Highs, and (2) pressure gradient (Δp) and upper winds associated with semipermanent Highs. Several other parameters were investigated, but proved of little value in improving the forecast method. These included 24-hour pressure changes in the Caribbean, temperature difference between 1000 and 850 mb., and the gradient wind over San Juan, P. R.

5. FORECAST SYSTEM FOR MIGRATORY HIGHS

DEVELOPMENT OF SYSTEM

Since migratory Highs affecting Puerto Rico almost invariably move off the east coast of the United States, the position and intensity of these Highs as they crossed the coastline and the subsequent winds in the forecast area were investigated. Migratory Highs were tested in the following manner: (1) all surface maps for the winters of 1955–56 and 1956–57 were reviewed and the track and central pressure were plotted for every migratory High moving off the east coast of the United States (2) the valve of Δp (measured between 15° N. and 25° N.) on each synoptic map was plotted beside the corresponding position of the migratory High; (3) the position of a migratory High that coincided with $\Delta p \geq 9$ 24 hours later was circled; and (4) a line was drawn through eastern United States just west of all these circled positions. This line, together with the coastline, delineated an area of the United States where migratory Highs had the potential of creating $\Delta p \geq 9$. It also gave the central

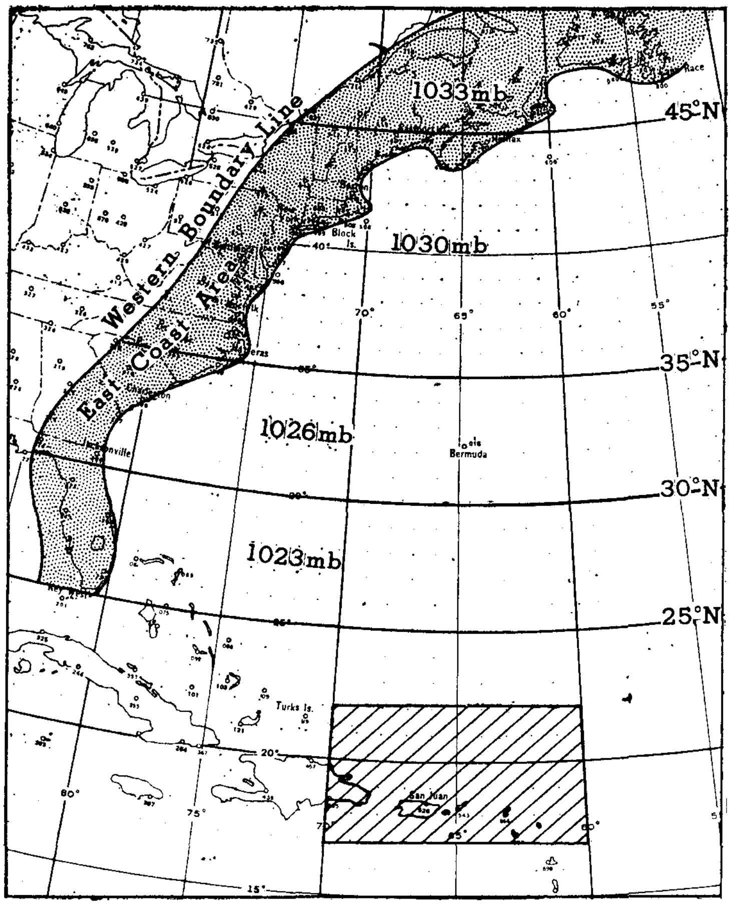

FIGURE 4.—Map showing east coast area (shaded) and the critical central pressure for Highs, by latitude zones, which must be exceeded to cause $\Delta p \geq 9$ over Puerto Rico in 24 hours. Hatched zone is area over which surface ship reports were averaged to obtain surface wind speeds and includes forecast area (Puerto Rico, the Dominican Republic, the Virgin Islands, the northern Leeward Islands, and the adjacent Caribbean and North Atlantic waters).

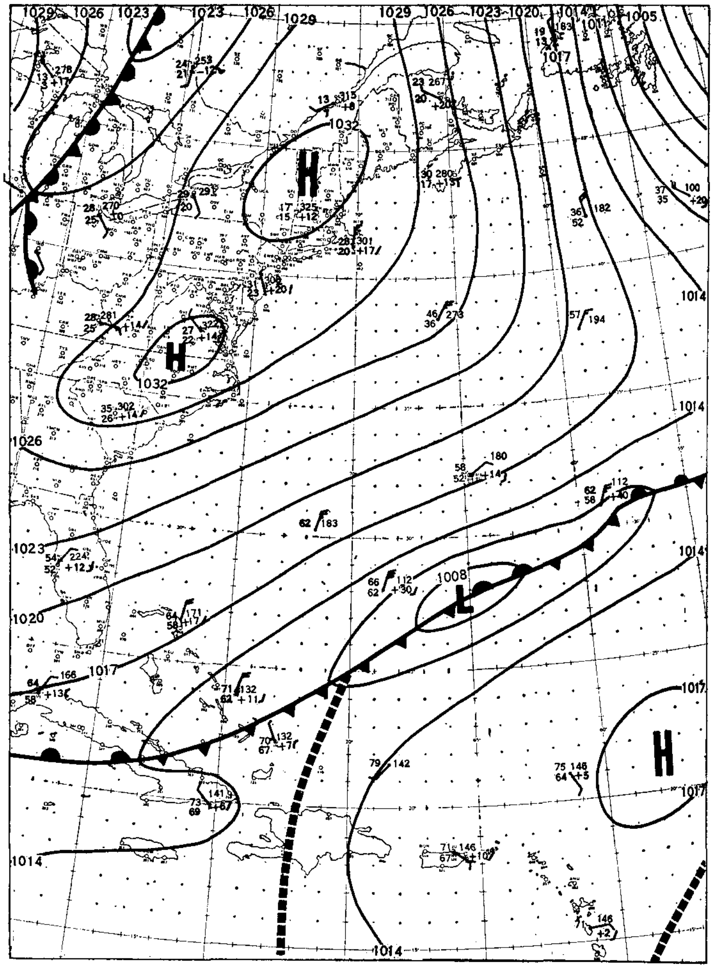

FIGURE 5.—Surface chart for 1200 GMT, February 22, 1957, depicting a well-defined trough between San Juan, P. R., and a migratory anticyclone in the east coast area.

pressures responsible for the eventual tightening of the gradient over the forecast area. James [1] has computed the mean central pressure of anticyclones over North America according to latitude. Table 1 shows that central pressures of anticyclones that eventually caused $\Delta p \geq 9$ were slightly higher than this mean and that the chances of a migratory High causing $\Delta p \geq 9$ depended on its intensity and latitude. The farther south the center is located, the weaker the High can be and still cause $\Delta p \geq 9$, and conversely, the farther north the center, the greater the central pressure has to be to produce $\Delta p \geq 9$.

TABLE 1.—*Central pressures of anticyclones at various latitudes*

Latitude (°N.)	Mean central pressure as computed by James [1] (mb.)	Central pressure which must be exceeded to cause $\Delta p \geq 9$ (mb.)
25-30	1023.5	1023
30-35	1024.5	1026
35-40	1026	1030
40-45	1027	1030
45-50	1028.5	1033

The central pressure which must be exceeded to cause $\Delta p \geq 9$ will henceforth be called the "critical" pressure. The area along the east coast of the United States and the critical central pressures are shown in figure 4. The western boundary of the area is within 200 miles of the coast south of 40° N. and within 250 miles of the coast north of 40° N.

Using the location and intensity of migratory Highs as forecast parameters, the following forecast rule was developed:

> If a migratory High with central pressure exceeding the critical value for the latitude moves across the western boundary line into the east coast area, forecast $\Delta p \geq 9$ (strong winds) in 24 hours unless a Low or well-defined trough is between the High and Puerto Rico.

Location and intensity of migratory Highs were used to forecast Δp rather than winds directly because of the deficiency of wind data on many charts. It has already been established that the pressure gradient may be used as a measure of the wind strength.

Cases where a low-pressure area or a well-defined trough was located between the high center and Puerto Rico

TABLE 2.—*Relationship of central pressures and latitude of migratory Highs entering east coast area in winters 1955–56 and 1956–57 to occurrences of pressure gradients $\Delta p \geq 9$ between 15° N. and 25° N. across Puerto Rico. x=cases in which High did not cause $\Delta p \geq 9$; numbers=time in hours to reach $\Delta p \geq 9$; *=cases in which Low or well-defined trough existed between high-pressure area and Puerto Rico*

Latitude (° N.)	Central pressure (mb.)				
	≤1023	1024–1026	1027–1030	1031–1033	≥1034
45–49	x		xxx	xxxx	30, 24, 12, 24
40–44	x		xx	*, 24	24, 36, 24, *
35–39	x	xxxxx, 18	xxx		x, 30
30–34	x	xx	x, 24		24
25–29	x	x, 24			

were excluded from the forecast rule because in those cases the gradient over the forecast area was not caused by the migratory High, but by another system. A well-defined trough was taken to be one with a southerly to southwesterly wind flow to the south and a northerly to northeasterly wind flow to the north. Figure 5 illustrates such a trough and shows a migratory High moving northeastward off the United States coast while the circulation over the Caribbean remains dominated by a semi-permanent high cell centered in the mid-Atlantic.

EVALUATION OF SYSTEM

Results of the forecast rule for migratory Highs applied to the initial data are shown in table 2. This table shows the relationship between central pressures of migratory Highs entering various latitude zones in the east coast area (crossing the western boundary line in fig. 4) and the future development (or nondevelopment) of $\Delta p \geq 9$. Entries to the left of the heavy line pertain to Highs with critical or below critical pressures for a given latitude, and entries to the right of the heavy line pertain to Highs with above critical pressures for a given latitude. Times when the forecast rule verified are shown as "x" marks on the left of the heavy line and as numbers (hours to reach $\Delta p \geq 9$) on the right of the line. An "x" on the right and a number on the left of the heavy line indicate times when the forecast rule failed. As an example, a High entering the east coast area at 40° N. with a pressure between 1031 and 1033 mb. is shown as causing $\Delta p \geq 9$ in 24 hours, while a High at 25° N. with pressure of 1023 mb. or less is shown as an "x" mark indicating $\Delta p \geq 9$ never occurred.

TABLE 3.—*Contingency table of results of objective forecast procedures for migratory Highs for initial data (December 1955, 1956; January, February, March, 1956 and 1957)*

		Forecast		
		$\Delta p \geq 9$	$\Delta p < 9$	Total
Observed	$\Delta p \geq 9$	12	1	13
	$\Delta p < 9$	3	26	29
	Total	15	27	42
Percent correct: 90 Skill score: .79				

TABLE 4.—*Relationship of central pressure and latitude of migratory Highs entering east coast area in winters 1953–54 and 1954–55 to occurrences of pressure gradient $\Delta p \geq 9$ between 15° N. and 25° N. across Puerto Rico. Symbols as in table 2*

Latitude (° N.)	Central pressure (mb.)				
	≤1023	1024–1026	1027–1030	1031–1033	≥1034
45–49			x	x x	*, 24
40–44	x x x	x	x x x	18	24
35–39	x x	x x x x x x x	x x x x x x, 36	36, 36, 30 30, 30	24, 18
30–34	x x x x x x x x	x x	x	18, 24	12
25–29	x x x x				

Highs north of 50° N. and south of 25° N. are not entered in table 2 since none of these caused $\Delta p \geq 9$. In fact, very few migratory Highs occurred south of 30° N.; the majority moved off the east coast between 35° and 50° N. This agrees fairly well with results obtained by James [1] in a study of 2,955 migratory anticyclones identified on the 1230 GMT surface weather map for North America. He found only 2 percent of the anticyclones were centered between 25° and 30° N.; the majority (56.5 percent) were located in the zone between 35° and 50° N.

As shown by table 2, the most frequent time required for $\Delta p \geq 9$ to develop after a High with an above-critical central pressure moved across the western boundary line into the east coast area was 24 hours. The average time was 25 hours. Thus, the forecast rule based on migratory Highs proved most satisfactory for periods of 24 hours.

When placed in contingency table form (table 3), the initial data gave an accuracy of 90 percent and a skill score of 0.79. The proportion of occurrences of $\Delta p \geq 9$ correctly forecast was 92 percent.

Although these scores are good they are not a real test of the method. Table 4, arranged in the same manner as table 2, indicates the results obtained when the forecast rule for migratory Highs which was developed from the 8 months of initial data was applied to an additional 8 months for the winters of 1953–54 and 1954–55. Results of these independent test data were similar to those obtained from the initial data. The most frequent time required for $\Delta p \geq 9$ to develop over Puerto Rico after an anticyclone with above critical pressure entered the east coast area was 24 hours and the average time was 25 hours. When placed in a contingency table (table 5) these test

TABLE 5.—*Contingency table of results of objective forecast procedures for migratory Highs for test data (December 1953, 1954; January, February, March, 1954 and 1955)*

		Forecast		
		$\Delta p \geq 9$	$\Delta p < 9$	Total
Observed	$\Delta p \geq 9$	13	1	14
	$\Delta p < 9$	1	40	41
	Total	14	41	55
Percent correct: 96 Skill score: .90				

data showed an accuracy of 96 percent and a skill score of 0.90. The proportion of occurrences of $\Delta p \geq 9$ correctly forecast was 93 percent.

Since there were no official Small Craft Warning forecasts available for comparison with the results from the initial and independent data, a further 12-month test was made using Daily Series Synoptic Weather Maps, Northern Hemisphere Sea Level Charts published by the U. S. Weather Bureau for the winters of 1944–45, 1951–52, and 1952–53. Winters of 1951-52 and 1952-53 were selected to make a continuous coverage of six winters when taken with the previously analyzed initial and test data. The winter of 1944–45 was picked at random. As the synoptic maps in these series are spaced 24 hours apart, this was a good test of the forecast system. A few migratory Highs could not be used as their centers passed through the east coast area in the interval between maps. Testing the forecast system with these data resulted in 53 cases of migratory Highs, but 8 of these had to be discarded as there were insufficient data to determine the pressure gradient accurately. The remainder gave an accuracy of 91 percent correct forecasts with a skill score of 0.75 which is in good agreement with the results obtained from the initial data.

While the terms $\Delta p \geq 9$ and strong winds have been used synonymously, $\Delta p \geq 9$ did not correspond to winds of 20 knots or more 12 percent of the time (fig. 2). Although it is believed that much of this failure may be due to incorrectly read gradients or inaccuracies and sparcity of surface ship data, nevertheless the number of correct forecasts using the migratory High forecast system must be reduced by 12 percent in order to determine the accuracy of the system in forecasting the onset of strong winds within 24 hours. Reducing the results by this percentage gives an accuracy of 81 percent for the initial data and 82 percent for the test data.

To make the migratory High forecast system as objective as possible, no attempt was made to forecast the future track or change in intensity of high centers. An effort to link the intensities of Highs with the time interval before $\Delta p \geq 9$ was reached was unsuccessful. During the investigation of migratory Highs, however, it was noted that most failures of the forecast system were due to Highs intensifying or weakening as they moved off the east coast of the United States, or to a High moving across latitude zones with different mean pressures. Even though the skill score obtained by this objective forecast system is probably slightly higher than could be expected in day-to-day forecasting, use of a little forecasting skill in foretelling the change of central pressure of Highs as they move off the United States coast should further improve the accuracy of the system. In fact, the migratory High forecast system was used during the past winter season (1957–58) with excellent results. Forecasters appear to have the most difficulty with Highs that are close to critical intensity. To provide for such cases, the forecast rule was modified to the extent that if a migratory High has a near-critical central pressure, the forecaster should wait an additional 6 to 12 hours to make sure that the High does not change its intensity and at the same time watch the pressure gradient over the forecast area to determine the trend. Even with a delay of an additional 12 hours, there is still ample time left to issue warnings should they be required.

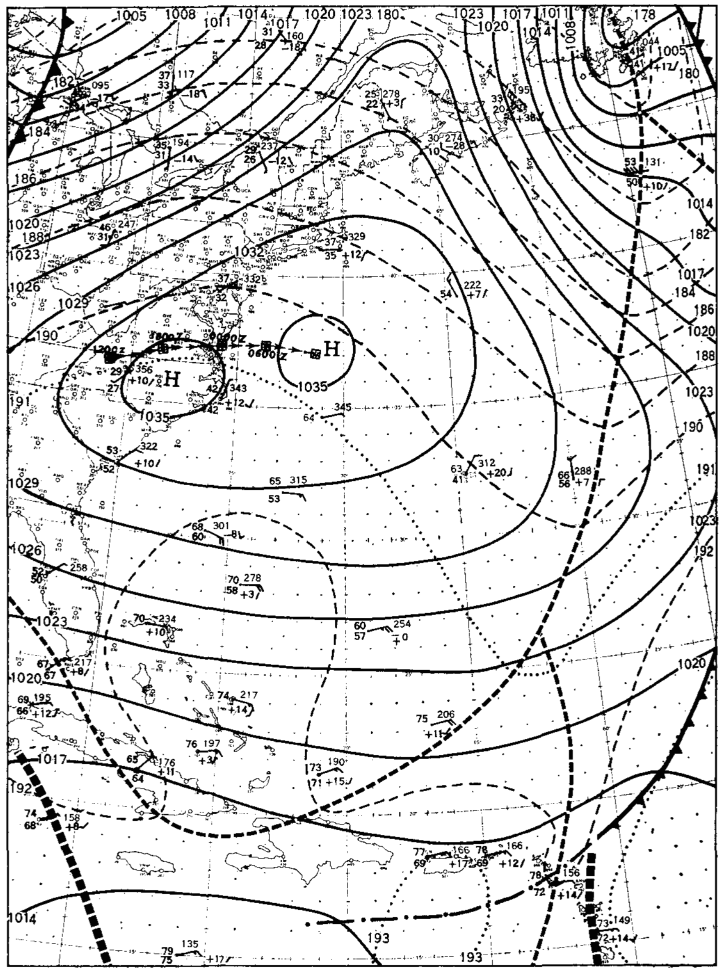

FIGURE 6.—Surface chart for 1200 GMT, December 23, 1957, depicting a migratory High with track of 6-hour past positions. 500-mb. chart for 1200 GMT, is superimposed as thin dashed lines.

6. FORECAST SYSTEM FOR SEMIPERMANENT HIGHS

DEVELOPMENT OF SYSTEM

Semipermanent warm Highs over the western North Atlantic may be due either to migratory cold Highs that gradually modify as they move over the relatively warmer area of the North Atlantic, or to the Azores High shifting to the west of its normal position. In either case, these Highs are normally centered south of 40° N. and west of 45° W. and create a strong gradient over the eastern Caribbean area as they intensify.

The basic difference between the migratory and semipermanent anticyclones is illustrated in figures 6 and 7. Figure 6 is a surface map of a typical migratory High after it crossed the United States coast and began to influence the eastern Caribbean; thin dashed lines show corresponding 500-mb. chart for the same date and time.

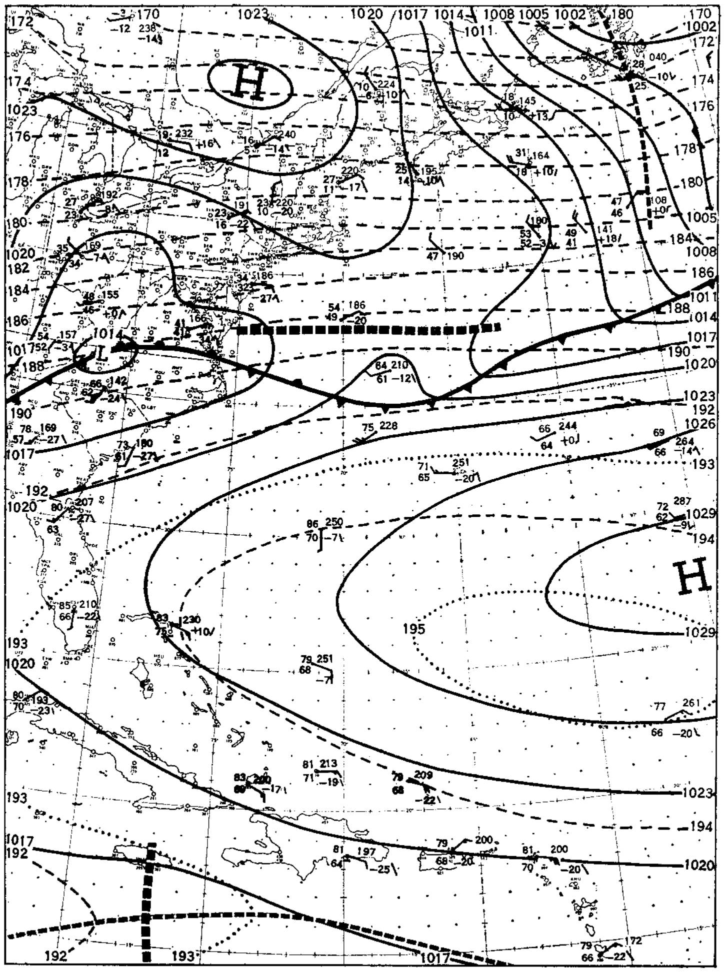

FIGURE 7.—Surface chart at 1800 GMT, February 1, 1957, showing a semipermanent anticyclone. 500-mb. chart for 1500 GMT, is shown by thin dashed lines. Note intense High corresponding to surface system.

It should be noted that the migratory High does not extend to the 500-mb. level as a well-defined closed center. Figure 7 is a surface map of a typical semipermanent High which has intensified north of the Caribbean. The corresponding 500-mb. chart is superimposed as thin dashed lines. This High is well marked at both the surface and 500 mb. and is quite intense aloft.

The trade winds over San Juan, P. R., as shown by Stone [2] are strongest between 750 and 1,000 meters (2,500 and 3,300 feet) and decrease downward due to surface friction. They also decrease upward until the westerlies are reached. This agrees with the observation of Riehl, Yeh, Malkus, and LaSeur [3] in the Pacific where wind speed decreased above and below the lower portion of the trade cumuli cloud layer (2,500 to 3,000 feet). However, an inspection of the upper winds at San Juan, P. R., revealed that there were occasions when strong surface winds were accompanied by increasing rather than decreasing upper winds above 3,000 feet. These occasions were investigated.

The upper wind parameter selected in this analysis was the maximum wind speed in the layer from 4,000 to 6,000 feet taken from the San Juan upper air data. This layer was above the normal trade wind maximum and proved satisfactory in showing those times when the trades increased rather than decreased above the 3,000-foot level. This parameter was tested only for $\Delta p=8$ since, as pointed out previously, $\Delta p=8$ is the only marginal pressure gradient. A stronger pressure gradient produces surface winds of 20 knots or more and a weaker gradient causes winds less than 20 knots. Little correlation was found between the upper wind parameter and the concurrent surface wind speed. However, when the upper wind parameter was compared with the surface wind speed 6, 12, 18, and 24 hours later, there was some correlation. The best correlation was in 12 hours.

It seemed logical to associate the times when the trade winds increased with intensification of semipermanent anticyclones in the western North Atlantic. Stone [2] pointed out that the axis of the Azores High slopes from northeast to southwest so that the northward shift of the High with the approach of summer has the effect of lifting the base of the westerlies. Consequently, in winter the base of the westerlies is low due to the southward shift of the Azores High. The times when the upper trade winds are most apt to increase with height are when the Azores High is farther north than normal for the season, or when a warm High is over the western North Atlantic.

Comparison between winds aloft over Puerto Rico in connection with a migratory cold High and a semipermanent High is shown in figures 8 and 9. The time cross section for December 22–25, 1957 (fig. 8), corresponds to a period when a migratory cold High moved off the continent and passed eastward north of Puerto Rico. On the time cross section the winds aloft decrease with height above the gradient level. With minor exceptions, therefore, the winds in the layer 4,000 to 6,000 feet are lighter than at lower levels. The base of the westerlies varies from 9,000 to 23,000 feet with a 2,000- to 3,000-foot transitional zone of weak winds between the easterlies and westerlies. The synoptic situation during this period is illustrated by the 1200 GMT surface map and the 1500 GMT 500-mb. chart for December 23, 1957 (fig. 6).

Figure 9 is a time cross section for January 28 to February 4, 1957. During this period a semipermanent High intensified in the western North Atlantic north of Puerto Rico. In figure 9 the winds aloft increase with height above the gradient level and the winds in the 4,000- to 6,000-foot zone are as strong or stronger than those at lower levels. The base of the westerlies is above 23,000 feet. The surface map and 500-mb. charts shown in figure 7 illustrate the position and intensity of the anticyclone causing these strong winds.

From the comparison between the two time cross sections it is apparent that the upper wind parameter will work best with semipermanent Highs since they are likely to cause strong winds aloft before strong winds are felt at the surface. To test the upper wind parameter with $\Delta p=8$, it was necessary to divide the data into

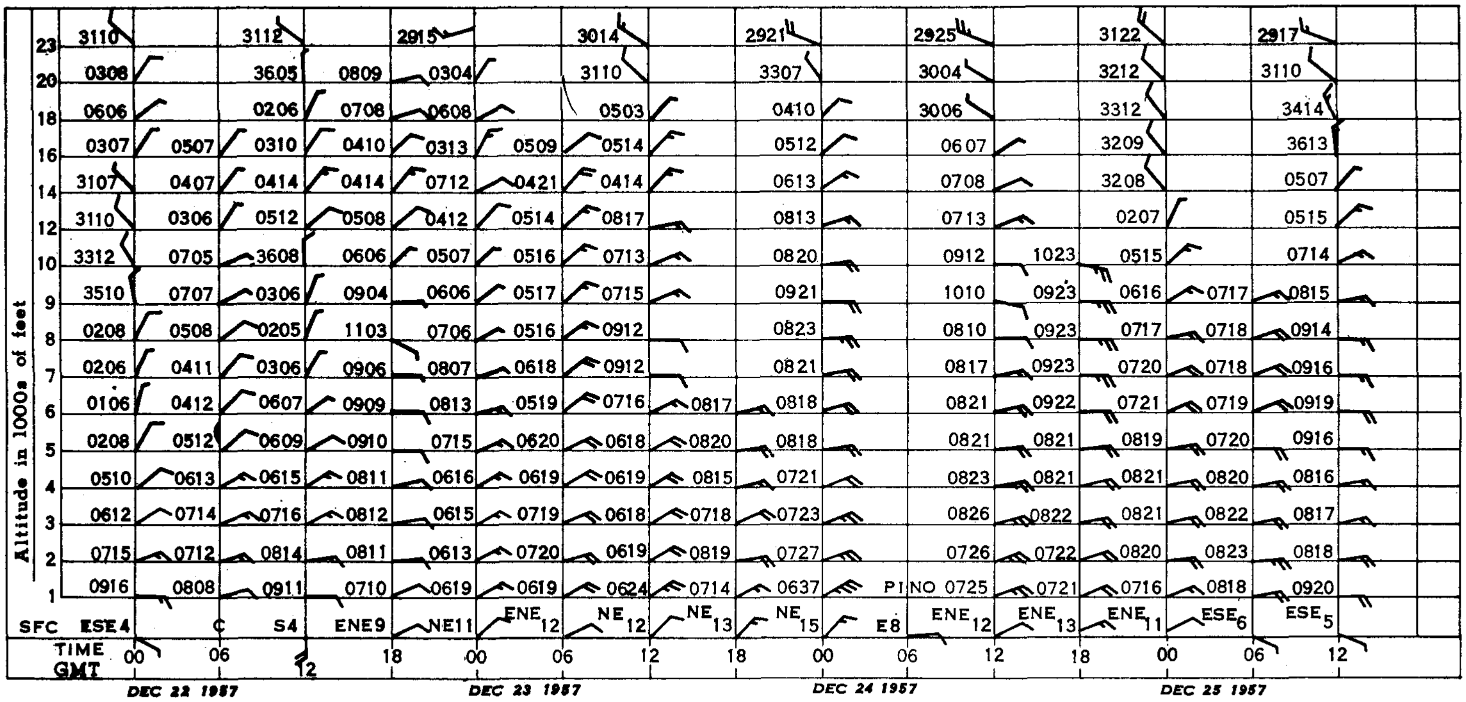

FIGURE 8.—Time cross section of winds at San Juan, P. R., from 0000 GMT, December 22, through 1200 GMT, December 25, 1957. Full barb on wind shaft equals 10 kt.; half barb equals 5 kt. Numbers to left of each wind are exact velocities with first two digits representing direction in tens of degrees and last two digits representing speed in knots. (See fig. 6.)

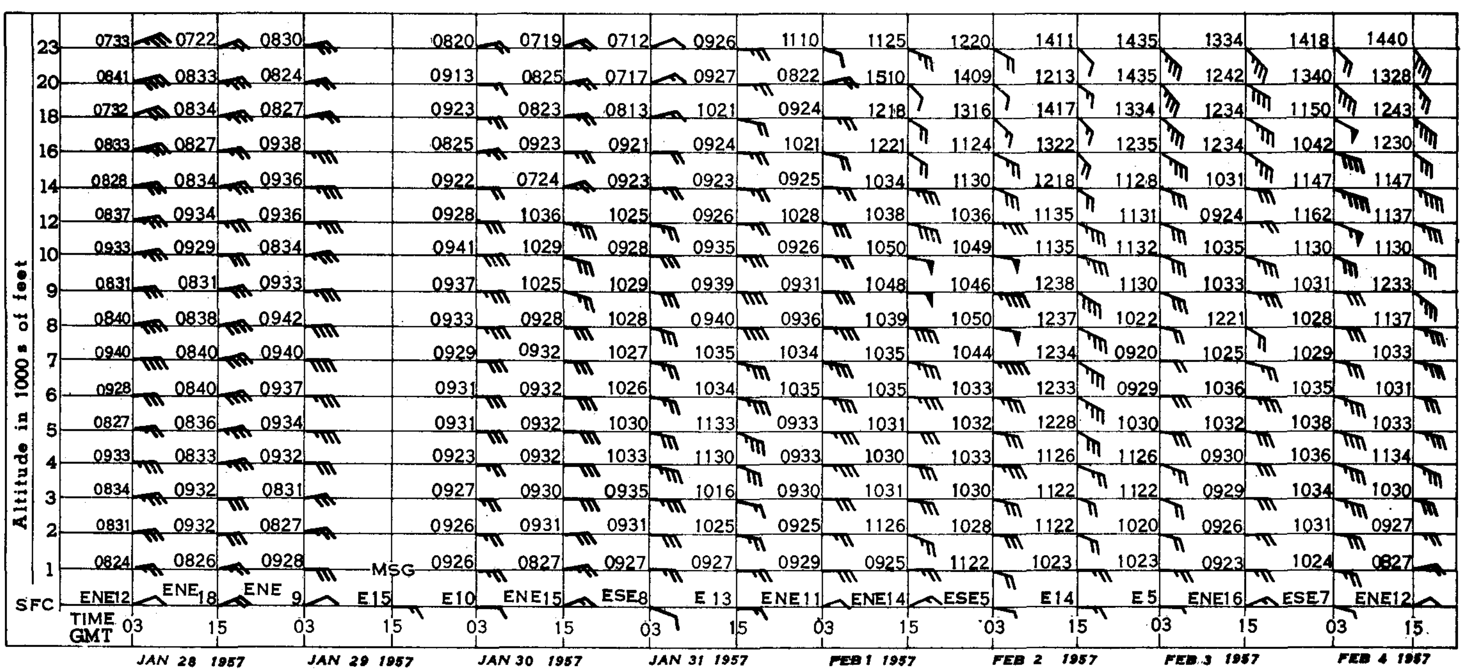

FIGURE 9.—Time cross section of winds at San Juan from 0300 GMT, January 28, through 1500 GMT, February 4, 1957. (See fig.7 .)

migratory and nonmigratory cases. All occasions with $\Delta p=8$ were listed with their corresponding upper and surface winds; then the surface map for each occasion was inspected and cataloged as either migratory or nonmigratory. If an anticyclone was cold and did not extend as a well-defined closed center to 500 mb. and if its track showed a movement off the continent, it was classified as a migratory High; if an anticyclone was warm and extended as a well-defined center to 500 mb. and had not recently moved off the continent, it was classified as nonmigratory.

The winter of 1956–57 was used for development purposes. Using only data for semipermanent Highs and $\Delta p=8$, the upper wind parameter (maximum wind speed

Table 6.—*Contingency table of results of objective forecast procedures for semipermanent Highs for initial data (December 1956; January, February, March, 1957)*

		Forecast		
		Winds ≥20 kt.	Winds >20 kt.	Total
Observed	Winds ≥20 kt.	18	2	20
	Winds <20 kt.	5	11	16
	Total	23	13	36
Percent correct: 81	Skill score: 0.59			

Table 7.—*Contingency table of results of objective forecast procedures for semipermanent Highs for test data (December 1953, 1954, 1955; January, February, March, 1954, 1955, 1956)*

		Forecast		
		Winds ≥20 kt.	Winds <20 kt.	Total
Observed	Winds ≥20 kt.	13	4	17
	Winds <20 kt.	2	27	29
	Total	15	31	46
Percent correct: 87	Skill score: 0.71			

between 4,000 and 6,000 feet) was plotted against surface wind speed 12 hours later. It has already been shown that there was no significant correlation between the upper wind parameter and the current surface wind for $\Delta p=8$. Inspection of the plotted data showed best results with an upper wind of 25 knots. If the current upper wind parameter was above 25 knots, the surface wind was likely to be 20 knots or greater in 12 hours. Conversely, if the current upper wind parameter was 25 knots or less, the surface wind was likely to be less than 20 knots in 12 hours.

EVALUATION OF SYSTEM

Table 6 shows the results obtained from the development data. These data gave an accuracy of 81 percent with a skill score of 0.59.

It was not possible to compare the development data with the official forecasts since no records of Small Craft Warning forecasts were available. Instead the data were evaluated by analyzing data for the winters of 1953–54, 1954–55, and 1955–56 on a scatter diagram in the same manner as the development data. Table 7 based on this 3-year winter period shows an accuracy of 87 percent with a skill score of 0.71. As both the development data and check data are in good agreement and together cover a period of four winters, the upper wind and $\Delta p=8$ parameters may be considered useful forecast tools to predict strong surface winds associated with semipermanent Highs.

So far this upper wind method considered only semipermanent Highs because they appeared most likely to give significant results. To check the validity of using it for both migratory and semipermanent Highs, the same forecast method was applied only to migratory Highs for the 12-month period of the check data. The results are shown in table 8. This contingency table gave an accuracy of 66 percent with a skill score of 0.30 for migratory Highs. The difference in accuracy between the method applied to semipermanent Highs and to migratory Highs is enough to justify use of the upper wind parameter solely with semipermanent Highs. There were no other parameters investigated that showed as much forecast value as the upper wind and none in combination with the upper wind gave any forecast improvement.

Table 8.—*Contingency table of results of objective forecast procedures for semipermanent Highs applied to migratory Highs for test data (December 1953, 1954, 1955; January, February, March, 1954, 1955, 1956)*

		Forecast		
		Winds ≥20 kt.	Winds <20 kt.	Total
Observed	Winds≥20 kt.	10	17	27
	Winds<20 kt.	2	27	29
	Total	12	44	56
Percent correct: 66	Skill score: 0.30			

7. SUMMARY

The problem of forecasting strong winds over the coastal waters of the Dominican Republic, Puerto Rico, the Virgin Islands, and northern Leeward Islands during the winter was treated by dealing individually with the pressure gradient required to produce winds of 20 knots or greater and then with the synoptic conditions most likely to produce that gradient. When the pressure difference between 15° N. and 25° N. reaches or exceeds 9 mb. ($\Delta p \geq 9$), the winds should be 20 knots or greater. Combined forecast rules for predicting the onset of strong winds are as follows:

1. *Migratory Highs:* If a High moves across the western boundary (fig. 4) into the east coast area and its central pressure is—
   a. Above the critical value, 20-knot winds or greater should be expected in 24 hours.
   b. Below the critical value, no strong winds should be expected.
   c. At the critical value: (1) wait 12 hours; (2) check whether High is increasing or decreasing in intensity; (3) if central pressure goes above critical value 20-knot winds or greater should be expected in 12 hours; (4) if it goes below or remains at the critical value no strong winds should be expected, but the pressure gradient should be watched.
2. *Semipermanent Highs:* If a High develops or intensifies over the western North Atlantic:
   a. Watch until the pressure difference between 15° N. and 25° N. over Puerto Rico reaches 8 mb. ($\Delta p=8$).
   b. When the maximum wind speed in the layer

between 4,000 and 6,000 feet over San Juan exceeds 25 knots, forecast surface winds of 20 knots or greater in 12 hours.

Use of these forecast steps makes it possible to forecast the onset of strong winds over the coastal waters of the Dominican Republic, Puerto Rico, Virgin Islands, and northern Leeward Islands 12 to 24 hours in advance depending upon the synoptic situation responsible for the winds. The forecast systems for migratory and semi-permanent Highs both proved over 80 percent accurate in predicting strong winds 12 or more hours in advance. Observing and forecasting the trend in the pressure gradient over Puerto Rico, intensification or weakening of a High, or exceptional speed or direction of motion of a High might eliminate many of the "misses." A few minor causes of strong winds were not treated because there were too few cases even in the 4 to 6 years used in this investigation.

This study does not represent a complete answer to the problems of forecasting strong winds over Puerto Rico and adjacent areas. There are other possible approaches that have not been explored, but many of them might be less objective and more complicated than the present system. It is hoped that this study will prove as useful as the results would seem to indicate. Even though an objective system often works better for its originators than for subsequent users, the reason may lie in familiarity with the methods employed. Once the forecaster becomes acquainted with the system and uses it as described, the results should prove compatible with the accuracy and skill indicated both by the basic and test periods.

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